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Single sneutrino production in $\gamma\gamma$ collisions

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Abstract

We study the single production of sneutrinos with two leptons (or jets) via $\gamma\gamma$ collision in an R-parity (R_p) violating supersymmetric model. The subsequent decays of the sneutrino are also considered. The single production of sneutrinos may provide a significant test of supersymmetry and R_p-violation with flavour conserving and flavour changing final states. If such processes coming from R_p violation are not detected, the parameter space of the model will be strongly constrained at the future Linear Collider.

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I. Introduction

One of the experimentally crucial issues in supersymmetric models is whether the R-parity [1] is conserved or not. The R-parity ($R_p = (-1)^{3B+L+2S}$, where B, L and S denote the baryon number, lepton number and spin) is introduced to forbid the fast proton decay, and it implies that the lightest supersymmetric particle (LSP) is stable and superparticles can only be pair produced. However, the conservation of R_p is not a necessity [2] and it can be violated in many ways. Numerous new phenomena are possible, if R_p is violated [3], e.g. R_p-violation ($\not{R}_p$) may explain neutrino oscillations from atmospheric neutrinos observed in Super-Kamiokande [4].

Searching for signals of supersymmetry (SUSY) [5] is one of the main aims of a Linear Collider (LC). LC is considered to be good at detecting physics beyond the Standard Model (SM) with its cleaner background in comparison with hadron colliders. However, its C.M. energy ($500-1000$ GeV) is lower than that in the future hadron colliders. Thus, if the sparticles are heavy, producing a single SUSY particle is kinematically favored. In addition to the e^+e^- collider mode, the LC can, with the advent of new collider techniques, produce highly coherent laser beams being back-scattered with high luminosity and efficiency at the e^+e^- colliders [6]. In this paper we will concentrate on $\gamma\gamma$ collisions.

The R_p-violation constrained by the low energy experiments has been widely discussed [7]. At the lepton colliders, R_p violation may be detected directly in sparticle production [8] or decay [9], or indirectly [10]. The single production of sneutrinos from e^+e^- collision has been considered in [8], where the L-violating parameters λ involving the light

flavours dominate the process. The resonant production of sneutrinos and single chargino production via $\gamma\gamma$ collision has also been considered in [11], where it was found that it is possible to improve the bounds on the parameters of the $\not{R}_p$ model, if SUSY with $\not{R}_p$ is not detected. The resonant sneutrino production at Large Hadron Collider (LHC) has been considered in Ref. [12].

In this work we will consider the single production of scalar neutrinos accompanied by two leptons (or two jets) in $\gamma\gamma$ collisions,

$$\gamma\gamma \to \tilde{\nu} + l\bar{l}^{'}, \;\; \tilde{\nu} + q\bar{q}^{'}. \tag{1.1}$$

Each diagram in the process contains one R_p-violating coupling, see Fig. 1. We will assume that one of the couplings dominates and thus is the only one which needs to be considered. Furthermore, the couplings including the third generation are less strictly bounded, and we will consider only them in this work. Thus for us the relevant couplings and the corresponding experimental limits are (from Allanach et al in [7])

$$\lambda_{131} \lesssim 0.062 \times \tfrac{m_{\tilde{e}_R}}{100 \text{ GeV}}, \; \lambda_{231} \lesssim 0.070 \times \tfrac{m_{\tilde{e}_R}}{100 \text{ GeV}}, \tag{1.2}$$

$$\lambda^{'}_{322} \lesssim 0.52 \times \tfrac{m_{\tilde{s}_R}}{100 \text{ GeV}}, \; \lambda^{'}_{323} \lesssim 0.52 \times \tfrac{m_{\tilde{b}_R}}{100 \text{ GeV}}. \tag{1.3}$$

The bounds in (1.2) are found [13] from the measurements of $R_\tau = \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ and $R_{\tau\mu} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$, while the bounds in (1.3) come from [14] $R_{D_s} = \Gamma(D_s \to \tau\nu_\tau)/\Gamma(D_s \to \mu\nu_\mu)$.

The production cross section of the process in (1.1) is of similar magnitude than the resonant production cross section. The process may induce flavour-changing final states.

Unlike in the case of resonant production, we may distinguish between the R_p-violating sources from the final states, which is one of the major advantages of this channel compared to the resonant production. Since Higgs single production with two leptons (or two jets) is suppressed by Yukawa coupling, the signal process may well have bigger cross section than the SM background. The background induced by Z boson can be distinguished with different quantum numbers and is suppressed when we consider a proper invariant mass cut.

In section 2, the supersymmetric $\not{R}_p$ interactions and calculations of the cross sections for the processes (1.1) are presented and detection strategy is considered. In section 3 we present numerical calculations of the processes and possible signals are given. Our conclusions are given in section 4 and the expressions for the photon luminosity are given in the appendix.

2. Production and decay of $\tilde{\nu}$ with explicit R-parity violation

All renormalizable supersymmetric $\not{R}_p$ interactions can be introduced in the superpotential as [15]:

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{[ij]k}L_i.L_j\bar{E}_k + \lambda^{'}_{ijk}L_i.Q_j\bar{D}_k + \frac{1}{2}\lambda^{''}_{i[jk]}\bar{U}_i\bar{D}_j\bar{D}_k + \epsilon_i L_i H_u. \tag{2.1}$$

where L_i, Q_i and H_u are SU(2) doublets containing lepton, quark and Higgs superfields respectively, $\bar{E}_j$ ($\bar{D}_j$, $\bar{U}_j$) are the singlets of lepton (down-quark and up-quark), and i, j, k are generation indices and square brackets on them denote antisymmetry in the bracketted indices. We will consider only the L-violating trilinear terms in our calculations. The bi-

linear terms [16] $\epsilon_i L_i H_u$ would also contribute to the process. The additional contribution to the production of a sneutrino with fermions comes only through mixing of Higgses and sneutrinos. In addition to the mixing, this is suppressed by the small Yukawa coupling, except for the top quark. When one considers the effects of bilinear terms in the decay of the sneutrino, several other possibilities exist. The processes involving the bilinear terms require a seperate analysis altogether and we will not connect it in the context of our present paper.

In the following calculations we assume that the parameters λ and $\lambda^{'}$ are real. The Feynman diagrams of $\gamma\gamma \to \tilde{\nu} + l^- l^{'+}$ are presented in Fig.1, and the Feynman diagrams of $\gamma\gamma \to \tilde{\nu} + q\bar{q}^{'}$ will be similar. We can calculate the cross sections of the processes from these diagrams and then fold the cross sections with photon luminosity to get observable results in e^+e^- collider.

We also need to consider the decay channels of sneutrinos in order to discuss the experimental detection possibilities. There are two essentially different modes in our case for sneutrino decay: it may be the LSP, in which case the $\not{R}_p$ decays are unique, or it may decay to some of the neutralinos or charginos if they are lighter than the sneutrino.

If sneutrino is the LSP, it will decay through R_p-violating terms. With nonzero λ coupling, sneutrino will decay to two leptons and with nonvanishing $\lambda^{'}$ coupling sneutrino will decay to a quark pair. If we assume that λ or $\lambda^{'}$ including different flavours is nonzero, sneutrinos may even decay to different flavours of a lepton pair or a quark pair. Even in the flavour conserving case the background from Higgs is negligible. In order to distinguish

the signal from a Z boson decaying to two leptons, we have to consider the different spins of sneutrinos and Z boson and the subsequent angular distributions. When $m_{\tilde{v}}$ is not close to m_z, invariant mass cut may also be useful.

If the lighter neutralinos $\tilde{\chi}^0_{1,2}$ and the lighter chargino $\tilde{\chi}^{\pm}_1$ are lighter than the sneutrinos, then the R_p-conserving decay is possible. The possible decay channels are as follows:

$$\tilde{\nu}_i \rightarrow \tilde{\chi}^{\pm}_1 l^{\mp}_i, \; \tilde{\nu}_i \rightarrow \tilde{\chi}^0_{1,2}\nu_i. \tag{2.2}$$

If it is kinematically allowed, sneutrino can also decay as follows

$$\tilde{\nu}_i \rightarrow \tilde{l}^{\pm}_{iL} W^{\mp}. \tag{2.3}$$

In the rest of this section, we will assume the GUT relations between the $SU(2)$ and the $U(1)$ gaugino mass parameters, namely

$$\begin{aligned} M_2 &= \tfrac{\alpha_2}{\alpha_3} m_{\tilde{g}} \\ M_1 &= \tfrac{5}{3}\tan^2\theta_W M_2, \end{aligned} \tag{2.4}$$

where $m_{\tilde{g}}$ is the mass of the gluino.

We take as a representative point in the MSSM parameter space the following: $\mu = 500$ GeV, $\tan\beta = 10$, $m_{\tilde{g}} = 300$ GeV. The corresponding chargino and light neutralino masses used in our numerical calculations are as follows: $m_{\chi^0_1} \sim 42$ GeV, $m_{\chi^0_2} \sim 82$ GeV, $m_{\chi^{\pm}_1} \sim 81$ GeV, and $m_{\chi^{\pm}_2} \sim 513$ GeV. In our case only the decays in (2.2) are allowed. In Fig.2 we show the branching ratios of the decays of sneutrinos with parameter λ or $\lambda^{'}$ dominating.

We can see from the Fig. 2 that the R_p-violating decay of sneutrinos will be important if we take $\lambda_{131} = 0.062$, and even dominate when $\lambda^{'}_{322} = 0.52$. In the case of flavour-changing coupling, the signal events would be easier to detect. In the following we use an

R_p violating decay of $\tilde{\nu}$ as a main way to detect the process (see Fig. 3 and Fig. 4), which means that the signal events have four leptons or four jets with invariant-mass equal to the C.M. energy of the $\gamma\gamma$ collision.

However, we also need consider other decay modes if the R_p-violating parameters are small. In Fig.5 we have plotted the production cross section of sneutrinos with sneutrino decaying to $\chi^+ + l^-$ with $\lambda \sim 0.01$. In that case the final states include mainly four leptons and missing energy.

3. Numerical results

In our numerical calculations, we take the single-coupling assumption: only one λ or λ' coupling dominates at a time.

In Fig.3(a), we show the cross section of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + e^+e^-) \rightarrow e^+e^-e^+e^-$ as a function of mass of sneutrino $\tilde{\nu}_\tau$. We plot the Figure with $\sqrt{s_{ee}} = 500$ GeV (dotted line) and with $\sqrt{s_{ee}} = 1$ TeV (solid line). The values of the couplings used, $\lambda_{131} = 0.062$ and $\lambda_{131} = 0.03$ are denoted in the Figure. The cross section may be of the order of 0.1 fb for light $m_{\tilde{\nu}}$ if we take $\lambda_{131} = 0.062$ (present upper limit for $m_{\tilde{e}_R} = 100$ GeV). Even for an R_p-violating coupling $\lambda_{131} = 0.03$, one signal event with four leptons may be produced with $m_{\tilde{\nu}} = 110$ GeV[2] at LC with an integrated luminosity 500 fb^{-1}. Similarly, in Fig.3(b), we plot the cross section of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + e^+\mu^-) \rightarrow e^+e^+\mu^-\mu^-$ as a function of masses of sneutrino $\tilde{\nu}_\tau$ with the coupling of λ, where $\lambda_{231} = 0.07$ (present limit for $m_{\tilde{e}_R} = 100$ GeV). For light $\tilde{\nu}$, about 20 flavour-changing events may be produced with 500 fb^{-1} integrated luminosity.

[2]The present lower limits for sneutrino masses are $m_{\tilde{\nu}_2} > 84$ GeV and $m_{\tilde{\nu}_3} > 86$ GeV [18].

In Fig.4 (a), we plot the cross section of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + s\bar{s}) \rightarrow ss\bar{s}\bar{s}$ as a function of sneutrino mass $m_{\tilde{\nu}_\tau}$ with $\lambda^{'}_{322} = 0.52$, and similarly $\gamma\gamma(\rightarrow \tilde{\nu}_\tau b\bar{s}) \rightarrow bb\bar{s}\bar{s}$ with $\lambda^{'}_{323} = 0.52$ is plotted in Fig.4 (b). It is seen that with an integrated luminosity 500 fb^{-1} hundreds of signal events are produced if $m_{\tilde{\nu}_\tau} \lesssim 200$ GeV for $ss\bar{s}\bar{s}$. Also hundreds of flavour-changing signals ($bb\bar{s}\bar{s}$) for light $\tilde{\nu}_\tau$ are produced.

In our parton level Monte Carlo analysis we have used an angular cut of $5^0 < \theta < 175^0$ for the leptons/jets in the final states. A minimum energy cut of 1.3 GeV has been applied to the leptons/jets in the final states.

In Fig.5(a) and (b) the cross sections of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + e^+e^-) \rightarrow \tilde{\chi}_1^+\tau^-e^+e^-$ and $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + e^+\mu^-) \rightarrow \tilde{\chi}_1^+\tau^-e^+\mu^-$, with $\lambda_{131} = 0.01$ and $\lambda_{231} = 0.01$ respectively, are presented. We find that it may be possible to detect single sneutrino events even for smaller R_p violating coupling, where signals come mainly from R_p conserving decay.

Comparing with the results of single sneutrino resonant production [11], we find that the cross sections of sneutrino produced in association with two leptons or two jets are of similar magnitude and can even be larger. Especially for R_p violating coupling involving light flavours, this kind of processes involving a single sneutrino with two leptons or jets can be easily detected.

4. Conclusion

We have studied the single sneutrino production (accompanied by two leptons or two jets) and decay of sneutrino in $\gamma\gamma$ collisions, in the context of R-parity violating supersymmetry. The cross section for the processes, in the future LC experiments with e^+e^- C.M. energy

1 TeV, with sneutrino mass below 175 GeV is above 0.01 fb with $\lambda = 0.062$, and with sneutrino mass below 200 GeV is above 1 fb with $\lambda^{'} = 0.52$, allowed by experimental limits. Even for much smaller R_p violating couplings, sneutrinos may be detected with their R_p conserving decay mode. We can also detect the flavour-changing final states if relevant R_p violating couplings are close to the present experimental limits. If we cannot find any such signals from the experiments, we could improve upon the present upper bounds on λ and $\lambda^{'}$ or increase the lower limit on sneutrino mass.

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Appendix

$\gamma\gamma$ collision

In order to get the observable results in the measurements of snutrino production via $\gamma\gamma$ fusion in e^+e^- collider, we need to fold the cross section of $\gamma\gamma \to \tilde{\nu} + l\bar{l}'(q\bar{q}')$ with the photon luminosity,

$$\sigma(s) = \int_{m_{\phi'}/\sqrt{s}}^{x_{max}} dz \frac{dL_{\gamma\gamma}}{dz} \hat{\sigma}(\hat{s}), \qquad (A.1)$$

where $\hat{s} = z^2 s$, $\sqrt{s}$ and $\sqrt{\hat{s}}$ are the e^+e^- and $\gamma\gamma$ c.m. energies respectively, and $\frac{dL_{\gamma\gamma}}{dz}$ is the photon luminosity, which is defined as [6]

$$\frac{dL_{\gamma\gamma}}{dz} = 2z \int_{z^2/x_{max}}^{x_{max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}(z^2/x). \qquad (A.2)$$

The energy spectrum of the back-scattered photon is given by [6].

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)}[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}]. \qquad (A.3)$$

taking the parameters of Ref. [17], we have $\xi = 4.8$, $x_{max} = 0.83$ and $D(\xi) = 1.8$.

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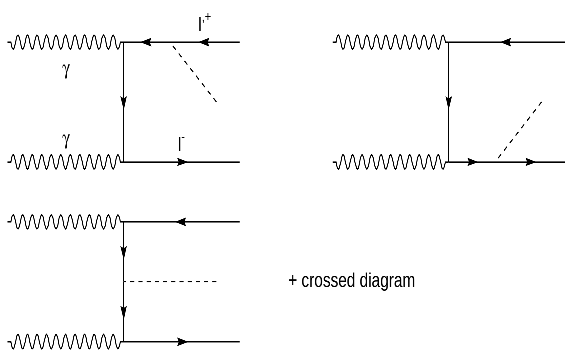

Figure 1: Feynman diagrams of $\gamma\gamma \to \tilde{\nu}_\mu l^- l'^+$. Dashed line represents sneutrino.

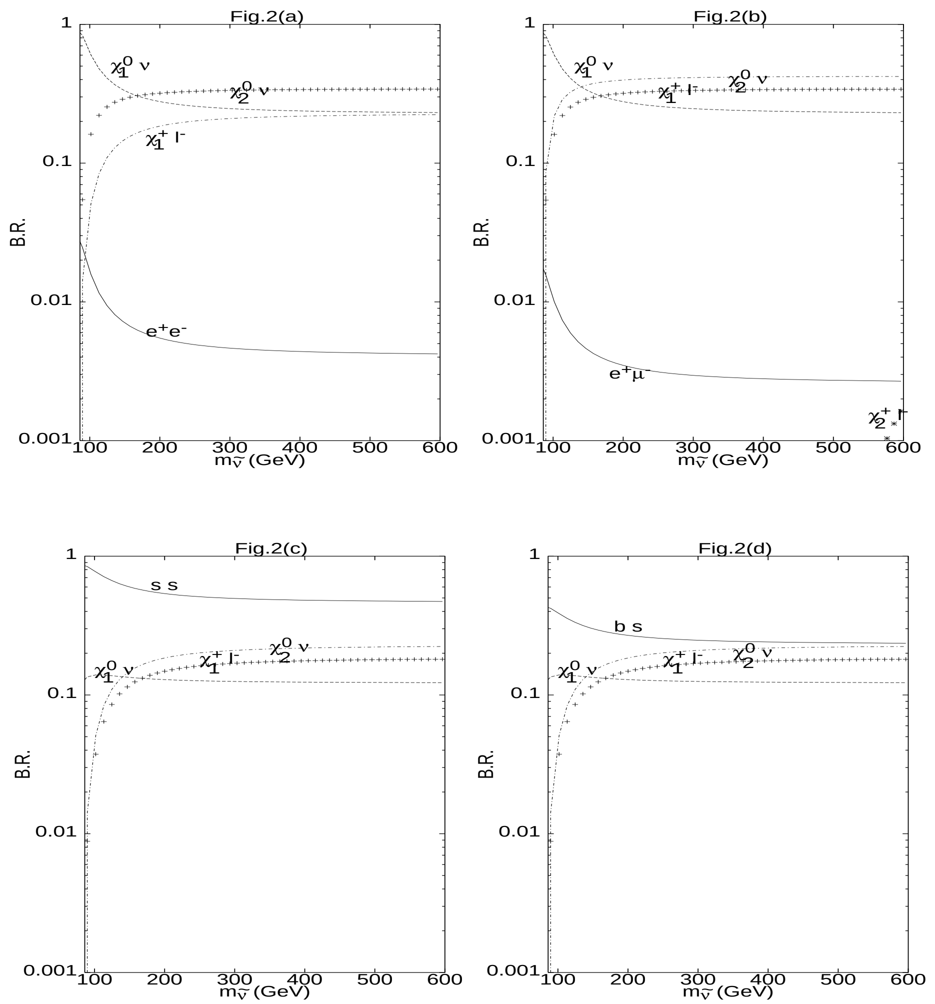

Figure 2: Branching ratios for sneutrino $\tilde{\nu}_\tau$ decays as a function of mass of sneutrino $\tilde{\nu}_\tau$, (a) with $\lambda_{131} = 0.062$, (b) with $\lambda_{231} = 0.07$, (c) with $\lambda^{'}_{322} = 0.52$, and (d) with $\lambda^{'}_{323} = 0.52$.

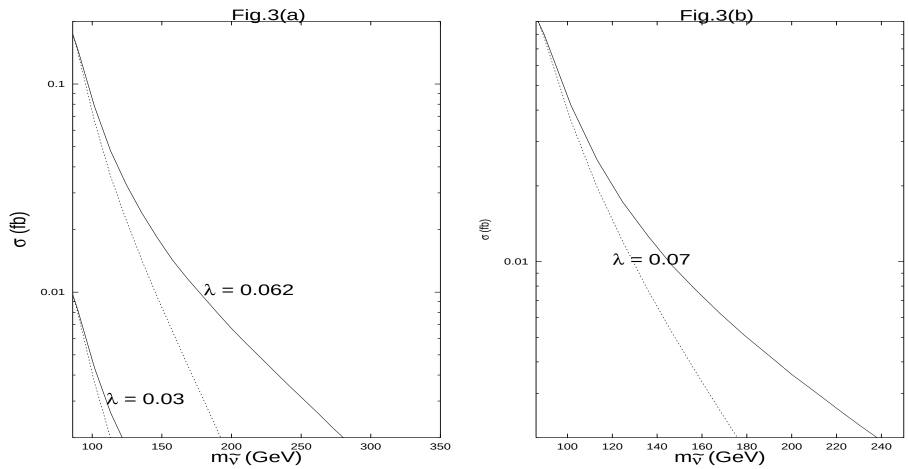

Figure 3: Cross section (a) of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + e^+e^-) \rightarrow e^+e^+e^-e^-$ with $\lambda_{131} = 0.062$ and $\lambda_{131} = 0.03$, and (b) of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + e^+\mu^-) \rightarrow e^+e^+\mu^-\mu^-$ with $\lambda_{231} = 0.07$. Both are as a function of mass of sneutrino $\tilde{\nu}_\tau$. Solid lines and the dotted lines correspond to the e^+e^- C.M. energy 1 TeV and 500 GeV respectively.

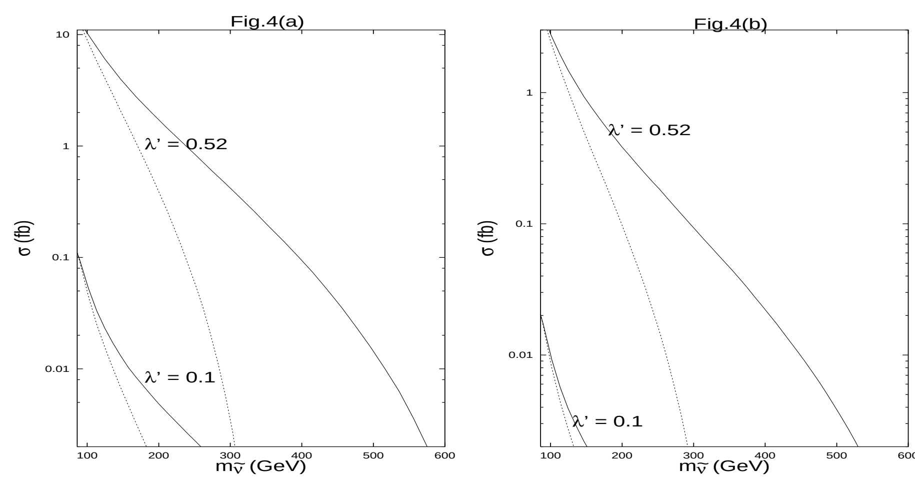

Figure 4: Cross section (a) of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + s\bar{s}) \rightarrow ss\bar{s}\bar{s}$ and (b) of $\gamma\gamma(\rightarrow \tilde{\nu}_\tau + b\bar{s}) \rightarrow bb\bar{s}\bar{s}$, as a function of mass of sneutrino $\tilde{\nu}_\tau$, and with $\lambda^{'}_{323} = 0.52$ and $\lambda^{'}_{323} = 0.1$. Solid lines and the dotted lines correspond to the e^+e^- C.M. energy 1 TeV and 500 GeV respectively.

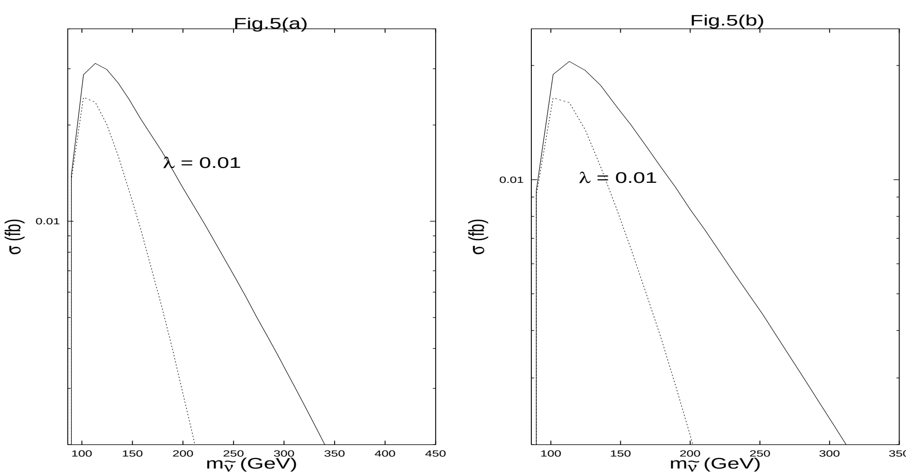

Figure 5: Cross section (a) of $\gamma\gamma \to \tilde{\chi}_1^+ \tau^- e^+ e^-$ with $\lambda_{131} = 0.01$, and (b) of $\gamma\gamma \to \tilde{\chi}_1^+ \tau^- e^+ \mu^-$ with $\lambda_{231} = 0.01$. Both are as a function of mass of sneutrino $\tilde{\nu}_\tau$. Solid lines and the dotted lines correspond to the e^+e^- C.M. energy 1 TeV and 500 GeV respectively.